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An evaluation of thermal breeding

von

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An evaluation of thermal breeding

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With 11 Figures in the Text

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Abstract

Under present technological and economic conditions, minimum fuel costs in thermal reactors are associated with systems having conversion ratios less than unity; however, when recycle of bred fuel becomes inexpensive (associated with rapid and inexpensive fuel fabrication, movement and processing), minimum fuel costs appear to occur with reactors having relatively high breeding ratios. Although the thorium cycle permits a higher breeding ratio than the uranium cycle, the fertile material and reactor concept which gives minimum fuel costs under present conditions is not clearly defined. This is due in part to inadequate information on the variation of eta with energy for the various fuels, particularly the eta values of Pu^{239} and Pu^{241}, and to uncertainties in economic factors.

Development of an "advanced" technology which permited inexpensive recycle of bred fuel would decrease the fuel cost in converter reactors as well as in breeders, and increase the conversion or breeding ratio of minimum-fuel-cost systems. With such development, the minimum U.S. nuclear power level at which breeder reactors were required was 250 million kw(e) (or equivalent), if U.S. fuel reserves were limited only to low-cost fuels, and the lower estimate of reserves applied. However, prior to attaining this power level, an advanced technology can be justified on the basis of fuel-cost savings in converter reactors. Thus, emphasis should be placed on the development of an inexpensive fuel cycle rather than the development of a thermal breeder. At the same time, breeders will eventually be necessary to conserve low-cost fuel, and the long-term objective of fuel cycle development should be to obtain minimum fuel costs in breeder reactors with present fuel prices.

An evalution of thermal breeding

1. Introduction

Thermal breeding is associated with a net production of fissile fuel in thermal-type reactors. The economic desirability of breeding depends upon general economic factors, the reactor-physics features of various fuels, the availability of low-cost nuclear fuel, and on economic and technological conditions as a function of time. However, a complete evaluation of thermal breeding cannot be performed at this time, since insufficient information is available. In particular, the variation of capital costs as a function of reactor type and operating conditions needs to be resolved in order to gain a better understanding of the role of breeder reactors in reactor development. Thus, this presentation constitutes only a partial evaluation of thermal breeding, the obejctives being to emphasize the interplay of variables which need to be considered in breeder reactor evaluation, and to give some general perspective of reactor performance as a function of reactor type, fuel material, and economic conditions.

Two separate aspects will be discussed. The first considers the basis on which breeder reactor development should proceed; much of the information presented here concerns both fast and thermal reactors. The second aspect treats thermal reactors specifically, and concerns the following:

(1) the basic physics constants associated with various reactor fuels;

(2) the influence of moderator, fission products, and fuel isotopes upon breeding ratio; and

(3) the relationship between fuel cycle cost and breeding ratio as a function of technological and economic conditions.

2. Basis for Breeder Reactor Development

Breeder reactors have the important feature of producing more fissile fuel than they burn. Thus, fuel costs in such systems can be low even though the price of fissile fuel is high; as a result, much interest has been shown in breeder reactor development. However, the term "development" implies that the potentially low fuel costs associated with breeder reactors are yet to be achieved, and such is the case. This is due in part to the tendency for fuel inventory charges and

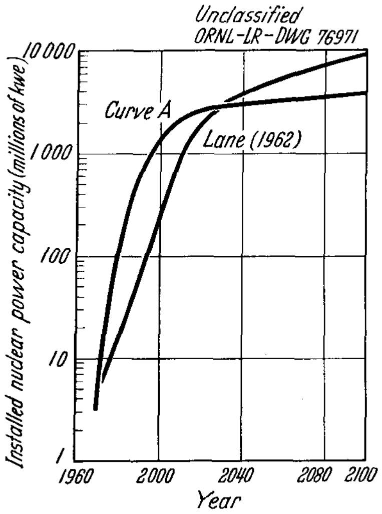

Fig. 1. USA projected nuclear power demand curves

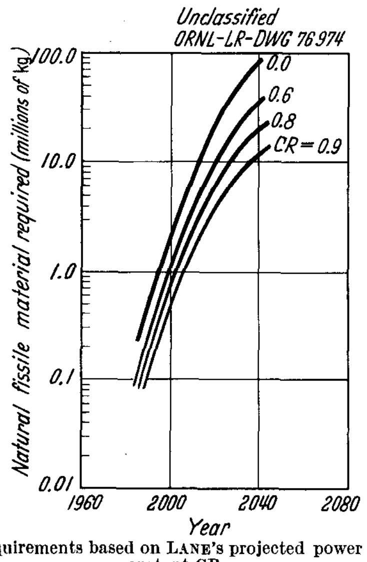

Fig. 2. Fuel requirements based on LANE's projected power growth and a constant CR

fuel fabrication-and-processing costs to be higher in breeder reactors than in nonbreeders, and for a given state of technology it is not necessarily true that breeder reactors will generate energy at lower costs than from other sources. In particular, if thermal breeder reactors are to be associated with *minimum-energy-cost* systems, a technology is required which can rapidly and economically move, process, and fabricate radioactive fuel during various parts of the fuel cycle. Such an "advanced technology" would normally develop with time, but there may be economic advantages in developing it at an accelerated pace.

The benefits to be derived from an economic-breeder technology can be considered in two ways; one concerns the economical extension of our fuel reserves. The key word here is "economical", since it is estimated [1] that low grade Th and U ores contain enough energy to supply the nuclear energy needs of an asymptotic world society of seven billion people for over 10^{10} years; at this stage of history it is immaterial whether 0·1% or 100% of this fuel is fissioned so long as economical energy is generated. Another viewpoint considers that breeder reactors have the capability of producing minimum-cost nuclear energy if an advanced technology were developed, even though low-cost nuclear fuel were available for long periods of time. Both viewpoints concern energy costs, and specifically involve fuel cycle costs; neither view excludes the other, but one may refer to a different period of time than the other. However, both require the development of an economical breeder technology; the associated investment in effort and money needs to be determined relative to conditions over a period of time and balanced against the benefits expected from such a technology.

2.1. Factors Influencing the Time Period Over Which Low-Cost Fuel Reserves are Available. In order to evaluate the time period over which low-cost nuclear fuel will be available, it is necessary to estimate the nuclear power capacity as a function of time, and also the quantity of low-cost fuel. Reference will be made to the work of KERLIN [2], who studied the nuclear fueling requirements of the United States as a function of the nuclear power growth and also as a function of the system conversion ratio or breeding ratio. (As used here, converter reactors are those which consume more fissile fuel than they produce, while breeder reactors produce more fissile fuel than they consume.) The two U.S. nuclear-power-growth estimates given in Fig. 1 were used; one was LANE's estimate [3], and it is designated as such. The other was based on an upper estimate by HARMS [4] up to the year 2000, along with an assumed extrapolation, and it is designated as "Curve *A*" in Fig. 1. Various combinations of average conversion ratios and system doubling times were considered; in all cases a specific power of 1000 kwe per kg of fissile fuel was assumed, and an average thermal efficiency of 36% was used. Fig. 2 gives the requirements for natural fissile material as a function of the system conversion ratio (CR), based on LANE's projected power growth. As would be expected, the required quantity of natural fissile material was significantly influenced by the average system conversion ratio.

The above fueling requirements need to be examined with respect to

(1) the available fuel reserves, and

(2) the cost of recovering various categories of reserves.

This requires information on uranium reserves, since uranium contains nearly all the natural fissile fuel which occurs on earth. The quantity and recovery costs of uranium ores are not known precisely, and in general the largest estimates of low-cost reserves correspond to the latest estimates. The estimates used here are those compiled by MCKELVEY [5] in 1961. Table 1 gives the estimated uranium resources for the USA and the world considering two recovery-cost levels, and specifically lists the associated natural-fissile-fuel content of the reserves. Although no quantity of material is listed in the \$ 10—\$ 30 per pound cost range, significant quantities probably exist at such recovery costs, if experience associated with other materials is applicable.

Based on Table 1, a minimum of about $3{\cdot}6 \times 10^6$ kg of low-cost U^{235} exists in the United States, and the amount may be as high as 18×10^6 kg. Using LANE's nuclear power-growth estimate, about 3·6 million kg of natural U^{235} would be required by 2010 if the average conversion ratio were 0·6; the same quantity would be required by 2015 if the conversion ratio were 0·8. The power levels at the above times and conversion ratios were 1000×10^6 kwe and 1500×10^6 kwe, respectively. Similar results were obtained when the power growth given by Curve A was used, indicating the importance of power level upon fueling needs, rather than the time dependence of power growth.

Table 1. *Estimated Uranium Resources as a Function of Cost* [5]

Recovery Cost \$/lb U_3O_8	U.S. Reserves		World Reserves	
	Metric tons U_3O_8	Millions of kg of U^{235}	Metric tons U_3O_8	Millions of kg of U^{235}
5—10	600,000—3,000,000	3·6—18·1	1,800,000—45,000,000	11—272
30—50	7,700,000	46	130,000,000	783

Since natural thorium does not contain fissile material, its usefulness lies primarily in its ability to produce a superior nuclear fuel, and by this means increase the energy recovery from natural fissile fuel. Generally, it appears there is more low-cost uranium than low-cost thorium; however, there are large quantities of both, and more thorium than uranium at the higher recovery costs.

In obtaining the results in Fig. 2, the conversion ratio was assumed to be constant over long time periods; however, this situation does not appear to be realistic. As soon as breeder reactors became economic power producers, they would replace converter reactors, but not all converter reactors would be replaced at one time. KERLIN [2] considered this situation, and his results will be used here. Specifically, the conversion ratio of a given power plant was assumed constant throughout its lifetime of 30 years, but after a given date all new plants operated with a fuel doubling time of 50 years[1]. For this case, converters would slowly disappear with time after the advent of economic breeders, but the fuel doubling time of the systems would not become 50 years until 30 years after building the first breeders.

The power level at which breeder reactors were first built was considered as a parameter, as was the conversion ratio prior to the building of breeders. Since the power-capacity doubling time became greater than 50 years during the time period considered (for the power-growth curves used here), only a finite amount of total natural U^{235} was required. Fig. 3 gives the results in terms of fuel requirements as a function of power level at which breeder reactors were initially built, with the initial conversion ratio and the power-growth behavior as parameters. Based on LANE's power-growth estimate and fuel reserves of 3·6 million kg of natural U^{235}, breeder reactors of 50-year doubling time would be needed at a power level between 30—110 million kwe (or equivalent[2]) for CR between 0·6—0·9. Although not shown in Fig. 3, at the time of changing to breeders only 0·1—0·15 million kg of natural U^{235} were required. Also, if breeders of about 20-year rather than 50-year doubling time were built, the above power-level range increased [2] to 200—250 million kwe, at which time fueling requirements were between 0·4—0·7 million kg natural U^{235}.

Based on the power-growth estimate given by Curve A in Fig. 1, the power level associated with required breeder operation would be higher than given above. For this case, again considering fuel reserves of 3·6 million kg of natural U^{235}, Fig. 3 shows that breeder reactors of 50-year doubling time would be needed at a power level between 150—530 million kwe for CR between 0·6—0·9 (at the time of changing to breeders, only 0·2—0·8 million kg of natural U^{235} were required). If breeders of about 20-year rather than 50-year doubling time were built, the power level at which breeders were required was between 300—800 million kwe [2], at which time fueling requirements were 0·6—1·3 million kg of natural U^{235}.

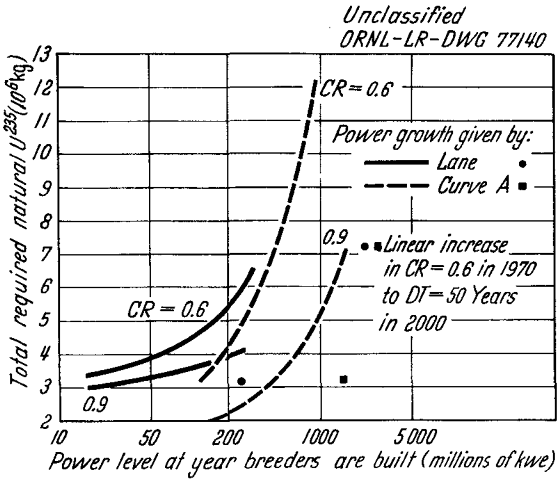

Fig. 3. Total natural U^{235} required VS. Power level at which breeders are built

In the above, a constant conversion ratio was assumed prior to building breeder reactors. However, advances in technology prior to the building of economic breeders would probably permit an increase in the conversion ratio of existing systems. Thus, it appears reasonable that the average conversion ratio would increase with time prior to the advent of economic breeders. If the system conversion ratio were 0·6 in 1970, and increased linearly with time until a doubling time of 50 years were attained in 2000, after which the DT remained at 50 years, KERLIN [2] found that the total required natural U^{235} was 3·2 million kg for both power growth curves considered here. These results are also given in Fig. 3 (as points) and indicate the importance of increasing conversion ratio prior to having economic breeders. As shown for

[1] For the assumed thermal specific power of 2500 kw (th) per kg of fissile fuel, a doubling time of 50 years corresponded to a breeding ratio of 1·013; decreasing the specific power by a factor of 3 and retaining the same doubling time would increase the breeding ratio to 1·038. Such breeding ratios appear to be readily attainable in many reactors.

[2] If nuclear energy is used for applications other than electrical energy generation, such use would need to be included in terms of an equivalent electrical capacity.

these cases, if economic breeders were initiated at a power level of 250×10^6 kwe based on LANE's growth estimate, or at 1500×10^6 kwe based on Curve A, total natural U^{235} requirements would be less than $3{\cdot}6 \times 10^6$ kg U^{235}. (Although not shown in Fig. 3, at the time the above power levels were reached, the associated fueling requirements were about $0{\cdot}6 \times 10^6$ and $2{\cdot}5 \times 10^6$ kg of natural U^{235}, respectively.)

Thus, based on the lower estimate of U.S. low-cost fuel reserves, the nuclear power level associated with the need to initiate breeder reactor operation appears significantly greater than the present U.S. total-installed electrical capacity. Also, the uncertainty in low-cost fuel reserves appears greater than the fueling requirements associated with a conversion ratio of 0·6 up to the time the nuclear power level reached about 2000 million kwe. Thus, the need to extend the U.S. low-cost reserves does not appear urgent. However, it may take appreciable time and effort to develop an economic breeder technology, and these conditions may justify breeder development at this time. Factors to be considered include the utilization of fuel reserves other than low-cost reserves, and the relationship between time and effort in developing an economic breeder technology. This latter factor is particularly difficult to evaluate, and is only mentioned here.

2.2. Economic Factors Associated with Thermal Breeder Development. The primary economic advantage of breeder reactors is associated with the excess fuel which can be produced. Thus, if fissile-fuel prices increased appreciably, breeder reactors could have significantly lower costs than converter reactors[1]. For example, based on LANE's estimated power growth and an average conversion ratio of 0·6, about 9·6 million kg of natural U^{235} would be required by 2020. If low-cost reserves were limited to $3{\cdot}6 \times 10^6$ kg U^{235}, use of higher-cost fuel could lead to a significant increase in fuel cost. Specifically, if enriched uranium were used which cost about \$ 10/g U^{235}, and the station thermal efficiency were about 40%, the fissile burnup costs would be about 0·50 mill/kwhe at a CR of 0·6; the fuel inventory charge would be about 0·14 mill/kwhe based on 10% annual charges, 80% load factor, and a specific power of 1000 kwe/kg fissile fuel. The burnup plus inventory charges would thus be about 0·64 mill/kwhe, and this part of the fuel cost would be directly related to the price of fissile fuel. For the case considered here, 6×10^6 kg of higher-cost natural U^{235} would be needed; however, the total fissile-fuel requirement up to 2020 would be 22×10^6 kg. Thus, only about 27% of the total fissile-fuel requirements would be obtained from the higher-cost natural fuel. If bred fuel retained the price associated with low-cost natural fuel[2], and the higher-cost natural fuel were four times as costly as the low-cost fuel, the above partial fuel cost would increase by 80%, or about 0·5 mill/kwhe. The total amount of money associated with such a cost increase would be about \$$7{\cdot}5 \times 10^{10}$ (about 150×10^{12} kwhe would have been generated by the year 2020, based on LANE's power growth estimate).

Increasing the CR would change the above figures, but similar results would be obtained at a later date. Thus, the above example illustrates two points, namely:

(1) if nuclear power remains competitive with other energy sources, initial use of higher-cost fuel reserves need not lead to a large increase in unit power costs; and

(2) a huge sum of money is associated with small unit power-cost savings if power levels are such as to exhaust low-cost fuel reserves.

Thus, a transition period from converter- to breeder-reactor operation could take place at the time low-cost fuel reserves were exhausted, without causing large unit power-cost increases due to fuel-cost changes. It is also evident that at the power levels being considered, a large investment could economically be made in breeder-technology development, if such development resulted in lower power costs than would exist without it[3].

Savings in unit fuel costs can also be accomplished in converter reactors, and so the above argument for breeder development can be applied to converter reactors as well. For example, fuel fabrication and processing costs associated with pressurized water reactors are presently about \$ 100/kg of fuel element; for a high-temperature-graphite reactor using fuel dispersed in graphite, the above costs are estimated to be about \$ 500/kg fertile material. Fuel exposures expected for the above fuel elements are about 20,000 Mwd/ton, and 100,000 Mwd/ton respectively, giving fuel fabrication and processing costs of about 0·5 mill/kwhe for both systems. Decreasing the above costs by a factor of three would effect a fuel-cost savings of over 0·3 mill/kwhe. Such a unit cost saving would lead to total dollar savings of 900—2700 million dollars over the time period during which nuclear power rose to 200 million kwe (considering the two power-growth curves considered here).

Based on the above, the economic need for fuel cycle development can be justified prior to the need for extending low-cost reserves (also, such development may be necessary if nuclear power capacity is to rise at projected rates). At the same time inexpensive fuel cycle charges are necessary if thermal breeders are to have low fuel costs, and may permit them to be economic at present fuel prices.

3. Nuclear Characteristics and Fuel Cost of Thermal Breeder Reactors

In many respects the above sections treated breeders as a class. The following discussion will relate primarily to thermal breeders; specifically, the breeding characteristics and the fuel-cycle costs will be

[1] A large increase in fissile fuel price may lead to nuclear power costs which are higher than the cost of power from alternative sources. This possibility should not be ignored, but it is difficult to take into consideration without introducing a number of additional parameters whose values are uncertain; it will not be studied here.

[2] Bred fuel would probably be retained within a given company's system, and could retain the price associated with low-cost natural U^{235}. If the bred-fuel price increased, the price differential would be larger than that derived here.

[3] The relations which exist between the amount of investment, technological area of development, time interval, and associated benefits are not very well understood. At the same time, they are needed in order to properly guide power reactor development, and also will help clarify the role of breeder reactors in producing economic nuclear power.

studied as a function of several variables and parameter values.

3.1. Energy Variation of Eta. The breeding potential of a given reactor is determined by the physics characteristics of the nuclear fuel. Of particular importance is eta (the number of neutrons generated per neutron absorbed in fuel), since it is directly related to the potential breeding ratio. For a specified value of breeding ratio, a high potential permits criteria used in reactor design and operation to be less severe than would otherwise be the case. As a result, fuels with the highest eta value have a basic advantage over other fuels. A single-energy value of eta, however, is insufficient to establish the potential breeding ratio. Rather, the energy variation of eta is required, since thermal reactors can have a significant number of neutron absorptions at energies above thermal, and "thermal" itself implies a range of energies. Fig. 4 shows the energy variation of eta for U^{233}, U^{235}, and Pu^{239}, respectively, based on present information [6] — [14]. Although not indicated, the accuracy of measurements is generally greater in the thermal and high energy regions; in the resonance energy region ($\sim$10—10^4 ev), the accuracy of given values may be relatively poor. For example, measurements by YEATER *et al.* [15] of the eta of $U^{233}(\eta^{23})$ over the 1—800 ev range gave values which were inconsistent with the results of critical experiments [14] covering the fast-and resonance-energy ranges; the η^{23} curve shown in Fig. 4 over the 30—1000 ev range is based on the results of the critical experiments. Also, the actual energy variations of eta in the resonance energy region are more oscillatory than those shown, and the smooth curves represent average values over finite energy bands.

The results in Fig. 4 clearly show the superior behavior of η^{23} up to energies of about 4×10^4 ev. Since relatively few reactions take place at energies above this value in thermal reactors, the results illustrate why the Th-U^{233} fuel cycle is considered the most promising one for thermal breeders.

The Pu^{241} nuclide is also a fissile fuel, and so the value of η^{41} as a function of energy should be included in Fig. 4; however, present information is insufficient to draw a representative curve of energy behavior. Of the three fuels considered above, and for the energy regions of interest, U^{233} appears to have the most accurately known eta variation, closely followed by U^{235}, with Pu^{239} a poor third.

3.2. Breeding Ratios. There are many nuclear factors which influence the breeding ratio of a reactor system; some of the more important ones are discussed here from the viewpoint of illustrating various effects. For the most part, reference will be made to work by CHERNICK and MOORE [16], LEVINE [17], and JAYE [18]. Eta values used by these investigators are not entirely consistent with the values given above; also, there were differences between the eta and cross section values used by the above investigators[1]. However, the differences are not significant as far as this discussion is concerned.

[1] JAYE's effective η^{23} values were about 0·05 less than those of CHERNICK and MOORE over moderator-to-fuel ratios of interest.

CHERNICK and MOORE [16] studied the breeding potential of U^{233}-fueled systems, and calculated the average η^{23} value[2] as a function of moderating power per U^{233} atom[3]. Fig. 5 is based on their results, and illustrates the influence of spectrum upon the average value of eta, with the spectrum being more thermal at the higher moderating-power values. Although the results given are for U^{233} fuel, a similar-shaped curve would be obtained for other fuels so long as the value of eta in the resonance-energy region (η_{res}), were less than the thermal value of eta (η_{th}). As shown in Fig. 4, such is the case for U^{233}, U^{235}, and Pu^{239}; it is probably true for Pu^{241} also.

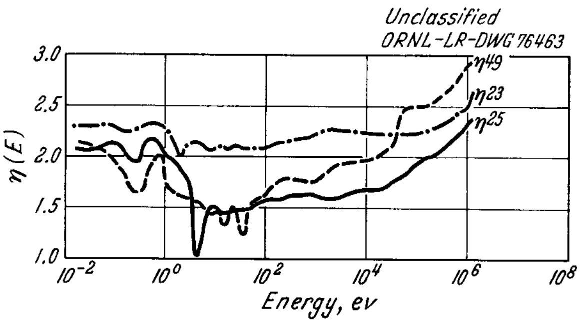

Fig. 4. Dependence of η on energy for U^{233}, U^{235}, and Pu^{239}

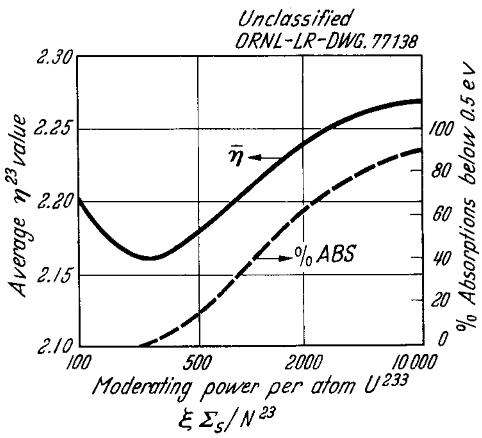

Fig. 5. Effect of neutron spectrum on average value of η^{23}

The potential breeding ratio is given by $\eta_{ave} - 1$, and for conditions associated with negligible neutron absorption by moderator and structure materials, Fig. 5 illustrates that the breeding ratio would increase with increasing thermalization (abscissa values for thermal reactors would be greater than 300). However, if the moderator had a significant thermal-absorption cross section, the breeding ratio would be modified. The effect of moderator absorption cross section upon breeding ratio was illustrated by CHERNICK and MOORE, who considered the neutron absorption associated with D_2O, graphite, Be, and H_2O moderators. Fig. 6 gives their results, and shows that as the moderator content increased, (reactor became more thermal), the breeding ratio passed through a maximum and then decreased with further moderator addition. Since D_2O has a very low absorption cross section, little breeding ratio

[2] Based on $\eta^{23}(E)$ weighted by the relative absorptions as a function of energy.

[3] The moderating power is defined as the product of the average logarithmic energy decrement per collision, ξ, times the average macroscopic scattering cross section, Σ_s.

penalty was associated with its use; however, it is more expensive than a material such as graphite, and economic factors have to be considered when choosing reactor materials.

If beryllium were used as a moderator, a substantial fast effect (ε) could be associated with the $(n, 2n)$ reaction; CHERNICK and MOORE indicate that $\varepsilon(n, 2n)$ has a value of about $1{\cdot}075 \pm 0{\cdot}02$. If a value of $\varepsilon = 1{\cdot}05$

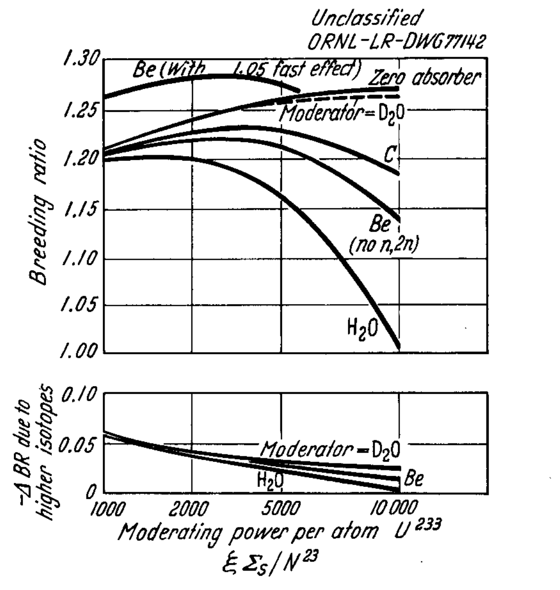

Fig. 6. Effect of moderator and higher isotopes on breeding ratio as a function of neutron spectrum (U^{233} fuel)

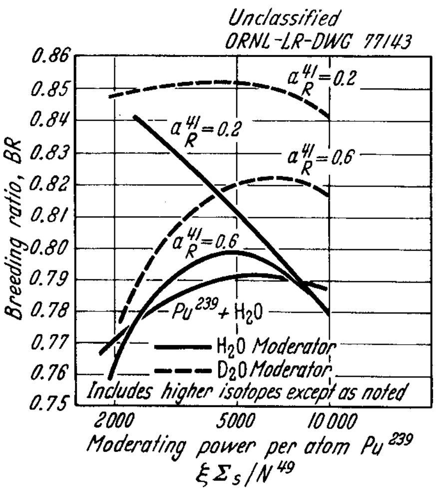

Fig. 7. Effect of moderator and resonance α^{41} value on BR in Pu systems

were considered, the resulting potential breeding ratio would be that given by the upper curve in Fig. 6. Thus, beryllium-moderated reactors have high potential breeding ratios; the lack of emphasis on the use of Be at this time is due to adverse economic factors.

As fuel is exposed to neutrons, higher isotopes of the fuel build up; these isotopes have absorption and fission cross sections, and so can alter the breeding ratio of a reactor system. Their effect on the breeding ratio was considered by LEVINE [17], who extended the work of CHERNICK and MOORE; his results will be considered below.

As used here, the breeding ratio refers to the ratio of fissile atoms produced to the fissile atoms destroyed[1]; thus, for the case of U^{233} fuel, where the higher isotopes are primarily U^{234}, U^{235}, and U^{236}, the breeding ratio would consider the effective eta values of U^{233} and U^{235}, the absorption cross sections of all fuel isotopes, and the fast fission factor of U^{234} and U^{236}. LEVINE took the above factors into consideration on the basis of equilibrium isotope concentrations, and calculated the change in breeding ratio due to the presence of higher isotopes as a function of moderating power and moderator material. The results for U^{233} fuel are given in the lower portion of Fig. 6. As shown, the presence of higher isotopes decreased the maximum breeding ratio by 0·03 to 0·04; thus, the upper curves in Fig. 6 should be lowered by the appropriate amount when higher isotopes are present in equilibrium concentrations.

LEVINE also studied the breeding ratio in plutonium systems; however, the accuracy of the results was relatively uncertain, due to the uncertainties in the eta values. Two different values (believed to correspond to low and high values) of $\alpha^{41}_{\mathrm{res}}$ (neutron captures per fission in Pu^{241}, averaged over the resonance-energy region) were used, namely 0·2 and 0·6; the value of $\alpha^{41}_{\mathrm{th}}$ was about 0·4 and η^{41}_{th} was about 2·2. Fig. 7 gives the results obtained, and shows the effects of moderator material, $\alpha^{41}_{\mathrm{res}}$ value, moderating power, and higher isotopes on the potential breeding ratio. Since Pu^{241} generally has better nuclear properties than Pu^{239}, inclusion of the higher isotopes generally resulted in a higher breeding ratio than was obtained from Pu^{239} alone. However, even under optimistic conditions ($\alpha^{41}_{\mathrm{res}}$ of 0·2, D_2O moderator), the maximum breeding ratio was only 0·85, which was considerably less than values obtained for the U^{233} cycle. At the same time the above results did not consider the presence of fertile material. The fast effect in U^{238} systems can be much greater than in Th systems, and so the results in Figs. 6 and 7 cannot be compared directly. The maximum ratio of fast effects for U^{238} relative to Th would be not greater than about 1·1. Applying this factor to eta, the 0·85 figure becomes 1·04; the appropriate BR for U^{233} (accounting for the higher isotopes in the U^{233} system) becomes 1·23 with D_2O moderator and 1·16 with H_2O. Thus, these results, which are believed to favor the U^{238}-Pu cycle more than would be the actual case, indicate that in thermal reactors, use of the U^{233} fuel cycle rather than the Pu cycle results in a substantially higher breeding ratio.

The buildup of fission products is another important consideration in the evaluation of breeding ratio. Even after relatively low fuel exposures, the breeding ratio can be significantly lowered by neutron absorptions in fission products. High-cross-section fission products such as Xe^{135}, Sm^{149}, and Sm^{151} can together lower the breeding ratio by 0·05—0·06 in typical reactors. Most of this poisoning is due to gaseous Xe^{135}; reactor systems which are able to remove xenon readily may

[1] While this definition is appropriate for thermal reactors where fissile fuels have about the same value, it is interpreted in different ways for fast reactors. In general, it appears best to define breeding ratio as the value of fuel produced to the value of fuel destroyed (economic breeding ratio). Such a definition would take into account the different values associated with different fuel isotopes, and would provide the information required in economic evaluation. If all fuel materials have the same value, the economic breeding ratio reverts to the conventional breeding ratio.

improve their breeding ratio by 0·03—0·05. The low-cross-section fission products do not reach saturation conditions rapidly, but they have the potential of reducing the breeding ratio by 0·5 or more at a given time. Calculations by LEVINE [17] showed that under equilibrium conditions after one fuel burnup, the decrease in breeding ratio could be 0·1—0·3. Several effective burnups may be desired in some reactors, and so fission-product poisoning could build up to high values.

Fission product poisoning is common to all fuels, and plays an important role in determining the breeding ratio of a given reactor. However, the gross absorption cross section associated with a given concentration of fission products varies with the fissile material; it appears that the gross cross section increases with the mass number of the fissile fuel, giving U^{233} fuel a slight advantage in this respect over the other fuels.

In addition to the above, other factors influence the breeding ratio of a reactor system. For example, the heterogeneity of the fuel influences the neutron losses to the moderator; more importantly, reactor heterogeneity influences the enrichment of the fuel required for criticality. Also, in thorium systems, neutron absorptions by Pa^{233} not only lose neutrons, they decrease fuel production. Such absorptions are directly related to the specific power and the Pa concentration. The time behavior of the reactor system is also important since under most conditions the nuclide concentrations will not correspond to steady-state values. Further, while the above studies were of a general nature, they did not include the influence of fertile material concentration on the average eta value; neither were detailed calculations made of self-shielding effects or of thermal-flux-spectra effects. These factors need to be included when studying specific systems [18].

Although the "potential breeding ratio" as measured by $\eta-1$ is a very useful quantity, it does not correspond to the breeding ratio, since neutron leakage and neutron absorptions in moderator, higher isotopes and structural materials cannot be eliminated in a practical reactor. The difference between the potential breeding ratio and the breeding ratio in a reactor system is determined by the economic conditions that apply, and this difference can be substantial. For example, in a typical high-temperature-graphite reactor, JAYE [18] found an average eta value of about 2·19 with U^{233} feed fuel, while the corresponding conversion ratio was 0·95; with feed fuel consisting of recycle uranium plus U^{235} makeup, the average eta value was 2·13 while the conversion ratio was about 0·88. These results indicate that the potential breeding ratio is not sufficiant for evaluating reactors and fuel materials. The next section will discuss the importance of economic factors in determining the breeding ratio of thermal reactors.

3.3. Breeding Ratio and Fuel Cycle Costs. The fuel cycle cost includes all items associated with the fuel cycle, such as fuel burnup costs, fuel inventory or lease charges, fuel fabrication costs, shipping costs, fuel and moderator inventory charges (including pre-exposure and post-exposure inventory), moderator losses, chemical conversion costs, fuel processing costs, and fuel losses associated with fabrication, chemical conversion and processing. High fabrication costs necessitate long fuel exposures to reduce their contribution to unit energy costs; however, a high breeding ratio requires short fuel exposures. Also, fuel processing losses and use of economical reactor sizes and reactor materials lead to lower breeding ratios than would be the case if economic factors were ignored. Thus, high breeding ratio and low fuel costs are not mutually consistant objectives, and some compromise in breeding ratio must be made in order to achieve minimum fuel cycle costs. The relative importance of some of these factors will be discussed below. Specifically, reactor performance will be studied as a function of fuel material, reactor type, operating conditions, and fuel-cycle charges (defined as costs

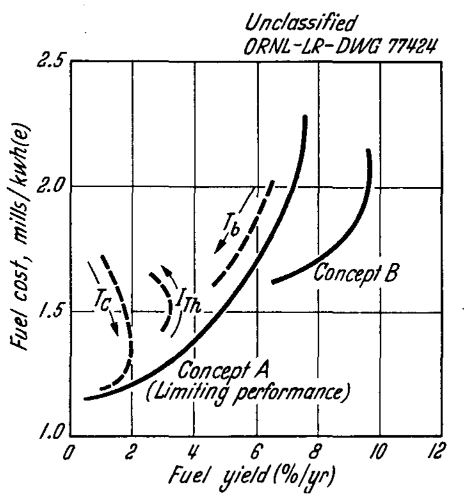

Fig. 8. Illustrative reactor performance as a function of operating conditions

associated with fuel fabrication, fuel movement, and fuel processing). The influence of reactor type and operating conditions on reactor performance will be presented first, considering the thorium fuel cycle; the results should also be indicative of the relative influence of these factors with U^{238} as the fertile material. In all cases, reactor performance will be measured in terms of fuel cycle costs and associated breeding ratio.

For a given reactor concept, the relationship between fuel cost and fuel yield is a function of economic conditions, nuclide concentrations, and fuel processing rates. For example, if a two-region reactor were operated with most of the fertile material in the blanket region and most of the fissile material in the core region, the reactor performance would vary with the core and blanket fuel processing rates, the processing costs, and with the concentration of fertile material in the blanket region. If one of the above parameters were varied and the others held constant, a specific relation would be obtained between fuel cycle cost and breeding ratio; if this procedure were continued and various parameter values were used, a series of curves would result. The envelope of all such curves for a given reactor is termed the limiting reactor performance. This is illustrated in Fig. 8, which plots the fuel cost as a function of fuel yield. (The fuel yield refers to the per cent of fissile inventory generated per year, in excess of needs; it is directly related to the specific power and the breeding gain, and so is positive only if the system has a breeding ratio greater than unity. Fuel yield is the inverse of fuel doubling time.) As shown, the reactor performance would be a function of reactor type (Concept A or Concept B), and of the economic conditions associated with items such as T_c, (the core cycle time), T_b (the blanket cycle time), and I_{Th} (the thorium inventory). In general, increasing the values of the above parameters would produce cost-yield variations similar to those indicated by the direction of the arrows in Fig. 8. The solid line would be the limiting reactor performance.

To illustrate the variation in the limiting performance as a function of reactor concept for a particular set of technological and economic conditions, reference will be made to the thermal-breeder evaluation of ALEXANDER *et al.* [19]. Five reactor concepts were studied, with each reactor having a core region con-

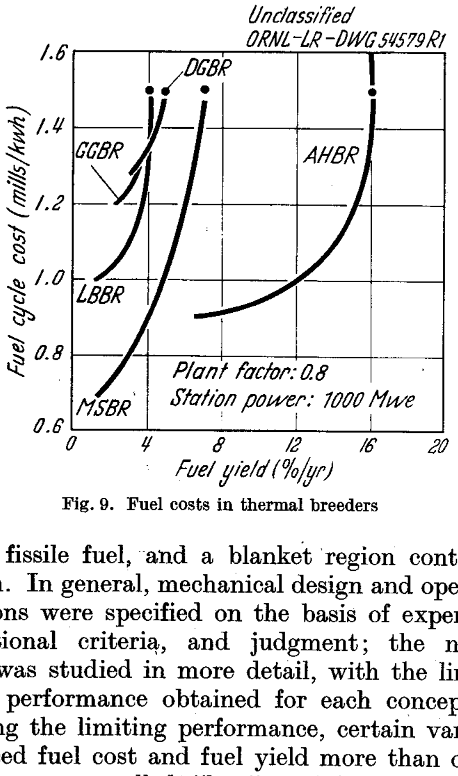

Fig. 9. Fuel costs in thermal breeders

taining fissile fuel, and a blanket region containing thorium. In general, mechanical design and operating conditions were specified on the basis of experience, conventional criteria, and judgment; the nuclear design was studied in more detail, with the limiting reactor performance obtained for each concept. In obtaining the limiting performance, certain variables influenced fuel cost and fuel yield more than others, and these were called "key" variables. Important postulates made for this study were:

(1) each station had a net electrical capacity of 1000 Mw provided by at least two reactors;

(2) all processing was performed in a reactor-site processing plant;

(3) the reactors were continuously fueled and processed and operated with equilibrium concentrations of nuclides; and

(4) the isotopic composition of the product fuel was the same as the average composition of the reactor plant.

A general, brief description of the five reactor systems and their operating conditions are given in Table 2. Inventory charges were based on price estimates and on the 1960 USAEC cost factors; i.e. \$ 17·1/g U^{235} for uranium of high enrichment; \$ 15/g U^{233}; fuel inventory charge at 4%/yr; inventory charge on other material at 12·7%/yr. Processing charges were based on estimates of costs of the required facilities, with charges varying with throughput and with fuel material. While processing costs for the different fuels were on as consistent a basis as possible, different future-technology conditions were associated with the different fuel cycles.

The limiting reactor performances obtained for the above reactor concepts are given in Fig. 9 (see Table 2 for definition of symbols), with the dots corresponding to limiting values of the fuel yield. As shown, the limiting performance varied significantly with reactor concept; more importantly, the results indicated little if any fuel cost advantage associated with breeding ratios above unity. This result emphasizes one of the basic difficulties of thermal breeder reactors today, namely; present economic and technological conditions are such that thermal breeder reactors have higher fuel cycle costs than do nonbreeders. This point is understood more clearly if it is remembered that the fuel-cycle technologies associated with the above reactor concepts represent extrapolations of present-day technologies. To illustrate this further, recent results obtained by ALEXANDER *et al.* [20] for a Molten Salt Converter Reactor (MSCR) are given below.

Table 2. *Characteristics of Five Thermal, Thorium Breeder Reactors*

AHBR: Aqueous-Homogeneous Breeder Reactor. Four reactors per station. Fuel was UO_2SO_4 in D_2O (473 — 554° F at 2000 psi). Processed by hydroclones and Thorex. Station efficiency was 27%. Zircaloy core vessel. ThO_2 pellets in blanket cooled by D_2O; processed by Thorex. Key variables were thorium cycle time and inventory. Fuel specific power was 0·7 — 1·1 Mw(e)/kg; thorium specific power was 6 — 7 Mw(e)/ton.

MSBR: Molten-Salt Breeder Reactor. Two reactors per station. Fuel was UF_4 in LiF-BeF_2 (1100 — 1300° F, 100 psi) in direct contact with graphite moderator. Processed by F_2 volatility, HF dissolution, with salt discard. Station efficiency was 42%. Heat exchanger and reactor vessel constructed of INOR-8. Blanket contained ThF_4 solution in LiF-BeF_2; processed by F_2 volatility with salt discard. Key variables were process and discard cycle times, and thorium inventory. Fuel specific power was 0·8 — 1·2 Mw(e)/kg; thorium specific power was 4 — 5 Mw(e)/ton.

LBBR: Liquid-Bismuth Breeder Reactor. Two reactors per station. Fuel was solution of U metal in Bi (1000 — 1300° F, 100 psi) in direct contact with graphite moderator. Fuel processed by molten-salt extraction. Station efficiency was 42%. Tantalum heat exchanger. ThO_2 slurry in blanket; processed by Thorex. Key variables were thorium cycle time and inventory. Fuel specific power was 0·5 — 0·7 Mw(e)/kg; thorium specific power was 6 — 11 Mw(e)/ton.

GGBR: Graphite-Moderated Gas-Cooled Breeder Reactor. Four reactors per station. Fuel was unclad-graphite fuel plates impregnated with UO_2. Fuel processed by leaching and Thorex. Cooled by helium (500 — 1500° F, 2000 psi). Station efficiency was 36%. ThO_2 pellets in blanket were cooled by helium, and processed by Thorex. Key variables were processing cycle times and thorium inventory. Fuel specific power was 0·5 — 1·0 Mw(e)/kg; thorium specific power was 5 — 10 Mw(e)/ton.

DGBR: Deuterium-Moderated Gas-Cooled Breeder Reactor. Four reactors per station. Fuel essentially same as GGBR. Station efficiency was 32% (some heat in moderator was not available). Heavy water was contained in Zircaloy calandria. Thoria pellets in blanket were cooled by D_2O and processed by Thorex. Key variables were processing cycle times and thorium inventory. Fuel specific power was 0·4 — 0·6 Mw(e)/kg; thorium specific power was 5 — 8 Mw(e)/ton.

The MSCR study considered a single-region, single-fluid reactor based on "near-term" technology. The molten salt was in contact with graphite moderator, with the fuel fluid containing both fissile and fertile material (the fuel salt was LiF-BeF_2 containing dissolved ThF_4 and UF_4). Fission products were removed from the reactor by withdrawal of fuel fluid; uranium was removed from this salt by means of the fluoride volatility process and returned to the reactor, but it was necessary to discard the other salt components when discarding fission products. Uranium recovery was accomplished in a central processing facility assumed to serve several reactors of the MSCR size (the power generated by the MSCR was 1000 Mwe, the same as that by the MSBR).

The key parameters influencing reactor performance of the MSCR were the core diameter, the volume fraction of fuel fluid in the core, the C/Th ratio, and the fuel processing rate. The fuel cost[1] was calculated as a function of the key parameter values, giving the limiting reactor performance shown in Fig. 10. The curve shown corresponds to about 2% fraction poisons associated with Xe^{135} and other gases. The minimum fuel cycle cost was slightly under 0·7 mill/kwhe, at a conversion ratio of 0·89. Although the MSCR calculations used different economic bases than were used in the MSBR study, the differences were not sufficient to significantly affect the relative performances of the two concepts. Comparison of Figs. 9 and 10 shows that for fuel yields greater than 2%/year, the MSBR had fuel cycle costs greater than the minimum MSCR fuel cost. Thus, fuel costs in a "near-technology" reactor were comparable with those in a breeder system using a "further-removed" technology. Also, even with MSBR technology, the minimum fuel cost appeared to occur at a breeding ratio less than unity.

The above discussion tends to paint a black picture relative to the economic virtue of thermal breeders prior to an increase in nuclear fuel prices; however, there is an important factor yet to consider, and that concerns fuel cycle charges (costs associated with fuel fabrication, movement, and processing). The breeder study of ALEXANDER *et al.* [19] assumed on-site processing plants which were relatively small and expensive. If fuel-cycle charges were very low[2], systems with minimum fuel costs would tend to be breeders; at the same time, fuel cycle costs in both converters and breeders would decrease with decreasing fuel cycle charges. This will be illustrated for the case of an aqueous homogeneous breeder reactor concept studied by ROSENTHAL *et al.* [21]; this concept was similar to that of the AHBR given in Table 2 and so the symbol AHBR′ will be used for it.

The AHBR′ was a two-region, heavy water reactor, with thoria slurry in the core and blanket regions; the blanket concentrations were 1000 g Th/liter and 4 g U^{233}/liter, while the thorium concentration in the core was 200 g/liter. The fuel price was \$ 16/g of fissile material; a 4%/yr inventory charge was applied to all materials except D_2O, in which case an effective rate of 9%/yr was used along with a D_2O cost of \$ 28/lb. The variable portion of the processing cost[3] was \$ 3/kg Th + \$ 0·5/g total U + \$ 0·35/liter D_2O. To illustrate the influence of fuel cycle charge on reactor performance, it was only necessary to vary the core processing charge, since the breeding ratio of the reactor varied primarily with the fission product poisons in the core region.

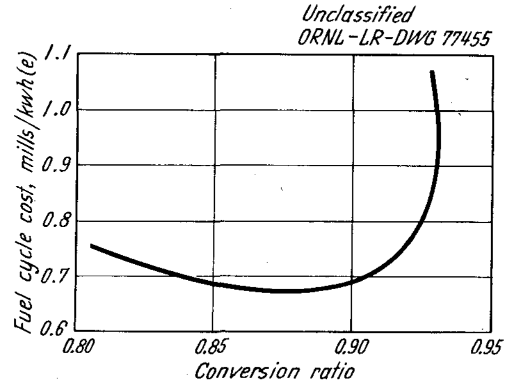

Fig. 10. Limiting performance of MSCR

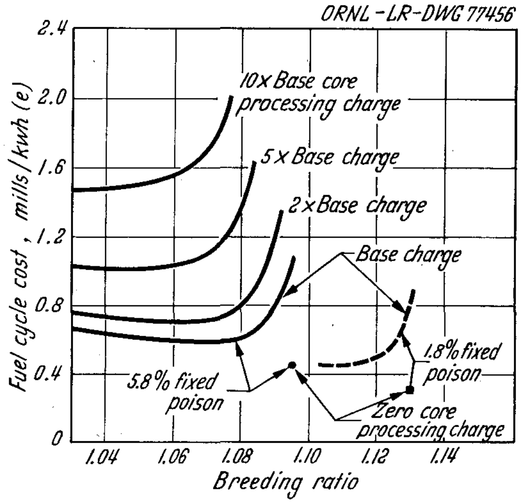

Fig. 11. Influence of core processing charge on reactor performance of AHBR′

Fig. 11 gives the reactor performance as a function of core processing charge, with the base charge equal to the variable charge given above; high-cross-section fission products were assumed to result in a fixed poison fraction of either 5·8% or 1·8%. As shown, increasing the processing charge increased the minimum fuel cycle cost and decreased the breeding ratio associated with minimum fuel costs. With zero core processing charge[4], the fuel cycle cost would be about 0·45 mill/kwhe with 5·8% fixed poisons, and

[1] In obtaining the fuel cost, the July 1962 USAEC price schedule was used (\$ 12/g U^{235} for U of high enrichment; about \$ 12/g U^{233}; and fuel lease rate of 4·75% per year); other economic factors were: inventory charge of 14·1%/yr on materials other than fuel; Li^7 cost of \$ 120/kg (99·99% Li^7). For the reference design conditions, fuel shipping costs were about \$ 10/kg Th and fuel processing costs about \$ 27/kg Th.

[2] Very low fuel cycle charges could be associated with central fuel-fabrication-and-processing plants which served many large power stations; alternatively, new processes may be developed which permit inexpensive processing and fabrication in smaller plants.

[3] In this study, the fuel processing cost constituted the fuel cycle charge.

[4] Zero core processing charge would not correspond to zero processing costs, since the blanket processing charge was held at the base rate. A zero core charge implies that core processing could be performed along with blanket processing without increasing processing costs. At the base rate and the specified conditions, blanket processing corresponded to a charge of about \$ 5·3/kg Th, and a cost of about 0·1 mill/kwhe.

Table 3. *Fuel Cycle Costs Obtained by Shanstrom for Several Reactors*

Case	Reactor Description	Fertile Material	Fuel Cycle Charge[1]		Fissile Loading kg	Fuel Enrichment[3] %	Fuel Cycle Costs[4] mills/kwhe		
			10^6/core	$/kg fuel[2]			A	B	C
1	H_2O cooled and moderated, stainless steel-clad fuel, 134 Mw(e), Intermediate fuel exposure	U Th	2·8 2·8	115 124	1120 910	4·5 4·0	2·6 3·2	2·0 2·4	2·2 2·7
2	D_2O cooled and moderated, Zr-2 clad fuel, 110 Mw(e), Intermediate fuel exposure	U Th	1·7 1·9	57 58	290 670	1·0 2·0	1·7 2·2	1·2 1·6	1·4 1·9
3	BeO moderated, He cooled, BeO cladding, 22 Mw(e), Intermediate fuel exposure	U Th	1·0 1·0	~163 not given	246 177	4·0 not given	2·3 1·9	1·9 1·5	2·0 1·6
4	Graphite moderated, He cooled, graphite cladding, 150 Mw(e), Batch fuel exposure	U Th	2·5 2·5	800 230	625 800	20 7·4	2·5 2·0	2·1 1·4	2·1 1·7
5	Same as Case 4 except graded fuel exposure	U Th	2·5 2·5	800 230	625 800	20 7·4	2·0 1·4	1·6 1·1	1·7 1·2

[1] Includes costs for fuel fabrication, movement, and processing.
[2] The term fuel includes fissile plus fertile material.
[3] Refers to % fissile material relative to fissile-plus-fertile materials; for The reactors, U enrichment was 95%.
[4] Three different cost bases were considered, as follows:
A. U^{235} price based on 1960 USAEC price schedule ($ 17·1/g U^{235} for 95% enriched U); $ 15/g U^{233}; $ 10·5/g Pu (as nitrate); 4% annual fuel lease charge.
B. U^{235} price based on July 1961 USAEC price schedule ($ 13·7/g U^{235} for 95% enriched U); otherwise same as Case A.
C. U^{235} price same as Case B; $ 12/g U^{233}; $ 8/g Pu (as nitrate); 4% annual fuel charge.

about 0·31 mill/kwhe with 1·8% fixed poisons; the corresponding breeding ratios were about 1·095 and 1·130, respectively. Thus, if fuel cycle charges were brought down to very low levels, reactors with relatively high breeding ratios could have minimum fuel cycle costs with present fuel prices. This view is substantiated by the results obtained by ROSENTHAL *et al.* [21] for one- and two-region homogeneous reactors, assuming the above base charges for processing. On the same cost bases, the minimum fuel cost of the two-region breeders was 0·5 mill/kwhe less than the minimum fuel cost of the single-region reactors, and the breeding ratio was 0·08 more in the two-region system (1·10 vs 1·02).

The above studies were of thorium fueled systems. As shown previously, use of thorium as fertile material in thermal breeders permits a higher breeding potential than use of U^{238}. However, uranium occurs in nature with some fissile material already present, while the same is not true of thorium. As a result, the cost of fissile material for U^{238}-fueled reactors would normally be less than for thorium ones. The resulting lower fuel inventory charges could offset the higher fuel-burnup costs, such that use of uranium rather than thorium produced lower fuel costs. This aspect is discussed below.

In a comparative study of uranium and thorium as fertile materials, SHANSTROM [22] evaluated the fuel costs of several reactor concepts. Table 3 gives a brief description of the various reactors studied, along with calculated fuel costs and associated conditions. The fuel cycle costs given for cost bases "A" corresponded to the minimal fuel cycle costs; however, for cost bases "B" and "C", parameter optimization was not performed, and the costs given corresponded to direct adjustment of the cost-bases-A results. In all cases, only the first fuel cycle was considered.

As shown in Table 3 the light-water reactor (Case 1) had lower fuel costs when U^{238} was the fertile material; in this case the lower U^{235} price associated with slightly-enriched uranium (rather than the highly-enriched uranium used with thorium) outweighed the better neutron economy attainable with the thorium cycle. Use of the uranium cycle also gave lower fuel costs for the heavy-water reactor (Case 2); here the uranium reactor had a lower fissile loading in addition to using lower-priced fissile fuel.

The BeO reactor (Case 3) had lower fuel costs when thorium was used. Here the reactor size was relatively small, and the neutron leakage relatively high; as a result, the higher thermal cross section of thorium relative to that of uranium led to a lower thermal-neutron leakage and a greater neutron economy for the thorium system, an advantage which would be less marked in a large reactor system. Also, homogeneous distribution of fuel in the moderator was considered for this case, and so the uranium enrichment of the U system was higher than would be the case if fuel lumping were permitted.

For the graphite-moderated, gas-cooled reactor (Cases 4 and 5), both batch and graded fuel exposure were considered[1]; however, fuel managment did not influence the relative results significantly. As shown in Table 3 for these cases, use of thorium rather than U^{238} gave lower fuel costs. This was due to the high uranium enrichment associated with the homogeneous dispersion of uranium in graphite; as a result of this

[1] Batch exposure corresponded to loading the reactor with fuel, and keeping the reactor critical by control-rod movement until it would no longer remain critical. Graded exposure corresponded to continuous fueling, such that neutrons were not absorbed by control rods. Intermediate fuel exposure corresponded to conditions intermediate between batch and graded exposure.

condition, the minimum fuel-cost uranium system had a low conversion ratio, a high unit U^{235} price, and a high unit fuel cycle charge (based on a constant fuel cycle charge per core loading).

The importance of fuel dispersion on relative fuel cycle costs in U^{238} and Th systems can be illustrated by comparing Cases 2 and 4 (or 5). Both reactor concepts had good neutron economy, but in one case the fuel was dispersed with the moderator, and in the other it was lumped in a fuel element. With fuel lumping (Case 2) the uranium system had lower fuel costs, and with homogeneous dispersion of fuel (Case 4) the thorium system had lower costs. If fuel lumping had been considered in Case 4, use of U^{238} would probably have given lower fuel costs, as indicated by results [23] obtained for a graphite-moderated, gas-cooled reactor using stainless-steel-clad, oxide-fuel elements. In the latter study (based on the July 1962 USAEC cost bases of \$ 12/g U^{235} for U of high enrichment, and 4·75% annual fuel lease rate), use of lumped-U fuel gave fuel costs which were about 0·5 mill/kwhe lower than those obtained with lumped-Th fuel. Thus, it appears that thorium reactors should use fuel uniformly dispersed in the moderator, while U^{238} reactors should use lumped-fuel elements. However, additional studies are needed to determine which fuel-element type permits lowest power costs.

SHANSTROM's study generally considered present-day technology along with present-day cost figures. In all cases, the reactors with minimum fuel costs had conversion ratios less than unity. Going to fuel cycles past the first would tend to improve the neutron economy, particularly in thorium systems. However, fuel fabrication costs would tend to be higher when using recycle fuel.

One more factor will be considered, and that is the fuel inventory charge. The above studies considered fuel lease rates of either 4 or 4·75%/year; however, under private ownership of fuel, the fuel inventory charge would probably be 8—10%/year. Increasing the fuel inventory charge would increase fuel costs in general, but would normally increase those in thorium systems more than in uranium systems. This was illustrated by BENNETT [24], who studied boiling-H_2O reactors (BWR with Zircaloy-clad fuel) and pressurized-H_2O reactors (PWR with stainless-steel-clad fuel) fueled with either Th or U^{238}; two different fuel-inventory charges were used in conjunction with two price schedules. The cost parameters used in the price schedules are given in Table 4; cost-schedule A corre-

Table 4. *Cost Parameters Used in Price Schedules*

Cost Schedule	Feed Mat'l Cost, \$/kg U	Sep. Work Cost \$/kg U	Tails Comp. w/f U^{235}	U^{235} Value at 95% Enrich. \$/gm U^{235}	Pu Price as Nitrate \$/gm	U^{233} Price as Nitrate \$/gm
A	23·50	37·29	0·00277	13·70	8·00	15·00
B	15·00	30·00	0·0030	10·25	6·00	11·20

sponded to an enriched-uranium price higher than that given by the present USAEC schedule, while cost schedule B corresponded to a lower price.

With the above price schedules, minimum fuel cycle costs were calculated with annual fuel-inventory charges of 4·75% and 12% (the 12% rate may be too high, but the results obtained indicate the effect of increased inventory charge on fuel costs). The results are given in Table 5[1]. As shown, increasing the inventory charge from 4·75 to 12%/year increased the minimum fuel cost of thorium systems 0·4—0·7 mill/kwhe more than that of uranium systems, for either price schedule.

Table 5. *Fuel Costs in 300 Mw(e) Reactors Fueled with Thorium or Uranium, Considering Different Interest Rates on Fuel, and Different U^{235} Price Schedules (Batch fueling; first cycle)*

Reactor Type	Cost Schedule (from Table 4)	Fuel Cost, mills/kwh(e) — Interest Rate on Fuel 4-3/4% — Fuel Type U	4-3/4% Th	12% U	12% Th
BWR	A	2·82	2·84	3·32	4·04
	B	2·39	2·45	2·81	3·37
PWR	A	2·65	2·49	3·31	3·69
	B	2·18	2·10	2·71	3·02

The above studies provide a basis for breeder evaluation, and also point out some important factors which need to be considered when evaluating reactors and fuel materials. In general, the relative importance of the various economic factors should be known as a function of economic and technological conditions. Thus, much additional work still remains to be done in the field of overall reactor evaluation, and should be done on a continuing basis so that new information can be incorporated as it becomes available.

4. *Summary and Evaluation*

Under present technological and economic conditions, minimum fuel costs are associated with reactors having conversion ratios less than unity. The fertile materials for these minimum-fuel-cost systems tend to be U^{238} in reactors having fuel separate from the moderator, and Th in reactors having fuel mixed with the moderator. Increasing the fuel inventory charge to values higher than the present rate of 4·75%/year would tend to increase the advantage of U^{238} over Th in heterogeneous reactors. However, additional work is required to properly evaluate the relative virtues of U and Th as fertile materials in different reactor concepts. Such studies would need more information about the variation of eta with energy; specifically, in the resonance energy region ($\sim 10-10^4$ ev) more accurate values of eta are needed for all the fissile fuels (U^{233}, U^{235}, Pu^{239}, and Pu^{241}), while in the thermal energy region better values for Pu^{239} and Pu^{241} are required.

When recycle of bred fuel becomes economical, the higher potential breeding ratio of thorium systems

[1] The Case 1 results in Table 3 may at first appear to be contradictory to the PWR results in Table 5; however, it must be remembered that different ground rules and different calculations were utilized in the two studies, and so a direct comparison of results cannot be made. For example, different economic bases regarding fuel price and unit fuel fabrication charge were used, and different fuel-managment schemes and out-of-reactor fuel inventories were assumed, which account for the different results. Such factors have to be consistent when comparing overall results, and the above illustrates the importance of understanding the bases on which specific results were obtained.

(about 1·2 vs 1·0 in uranium systems) would favour use of the thorium cycle rather than the uranium cycle. However, even with use of recycle fuel, minimum fuel costs would not correspond to breeding ratios greater than unity if fuel processing- and -fabrication costs were as high as \$ 40—\$ 50/kg fertile material. Under such conditions, single-region converter reactors based on present or near-term technology could have fuel costs comparable with two-region breeder reactors requiring a more-advanced technology. However, if fuel cycle charges were very low (equivalent to about \$ 5/kg fertile material) minimum-fuel-cost systems would tend to correspond to breeders, with two-region reactors having lower fuel costs and higher breeding ratios than one-region systems.

The economic need for breeder development can be related to the extension of low-cost nuclear fuel reserves. Based on estimates of U.S. nuclear power growth, if U.S. fissile-fuel reserves were limited to the lower estimate of low-cost reserves (i.e., $3{\cdot}6 \times 10^6$ kg U^{235}), breeder reactors would be required at a system power capacity of about 250 million kwe (or equivalent) in order that these fissile reserves be sufficient. Since there is a large uncertainty in the quantity of low-cost reserves, and since there are fuel reserves other than those associated with low-cost reserves, the above power level could be much greater than 250 million kwe. However, prior to attaining this power level, an "advanced" fuel cycle technology which permitted radioactive fuel to be fabricated, moved, processed and recycled rapidly and inexpensively could be justified on the basis of fuel-cost savings in converter reactors. Development of such an advanced technology could reduce fuel costs in all reactor types, increase the conversion ratio of minimum cost systems, and may permit thermal breeders to have minimum fuel costs with present fuel prices. It would also increase the power level associated with consumption of low-cost fuel reserves, and may be needed in order that nuclear power becomes and remains competitive with other power sources. Thus, it appears that during the next decade it is more important to develop an inexpensive fuel cycle than to develop a thermal breeder, although it is recognized that the two developments are related. At the same time, breeders will eventually be necessary to conserve low-cost fuel, and the long-term objective of fuel cycle development should be to obtain minimum fuel costs in breeder reactors with present fuel prices.

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